National Aeronautics and Space Administration

DRAFT ROBOTICS, TELE-ROBOTICS AND AUTONOMOUS SYSTEMS ROADMAP
TECHNOLOGY AREA 04

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FOREWORD

NASA's integrated technology roadmap, including both technology pull and technology push strategies, considers a wide range of pathways to advance the nation's current capabilities. The present state of this effort is documented in NASA's DRAFT Space Technology Roadmap, an integrated set of fourteen technology area roadmaps, recommending the overall technology investment strategy and prioritization of NASA's space technology activities. This document presents the DRAFT Technology Area 04 input: Robotics, Tele-Robotics and Autonomous Systems. NASA developed this DRAFT Space Technology Roadmap for use by the National Research Council (NRC) as an initial point of departure. Through an open process of community engagement, the NRC will gather input, integrate it within the Space Technology Roadmap and provide NASA with recommendations on potential future technology investments. Because it is difficult to predict the wide range of future advances possible in these areas, NASA plans updates to its integrated technology roadmap on a regular basis.

EXECUTIVE SUMMARY

Ongoing human missions to the International Space Station have an integrated mix of crew working with IVA and EVA robots and supporting autonomous systems on-board spacecraft and in mission control. Future exploration missions will further expand these human-robot partnerships. Unmanned science missions are exclusively robotic in flight, but are integrated with Earth based science and operations teams connected around the globe. Autonomous unmanned aircraft used in military operations are now seeing civilian and science applications, and the line between piloted aircraft cockpits and telerobotic command consoles continues to blur. Robots, telerobots and autonomous systems are already at work in all of NASA's Mission Directorates. NASA will see even more pervasive use of these systems in its future.
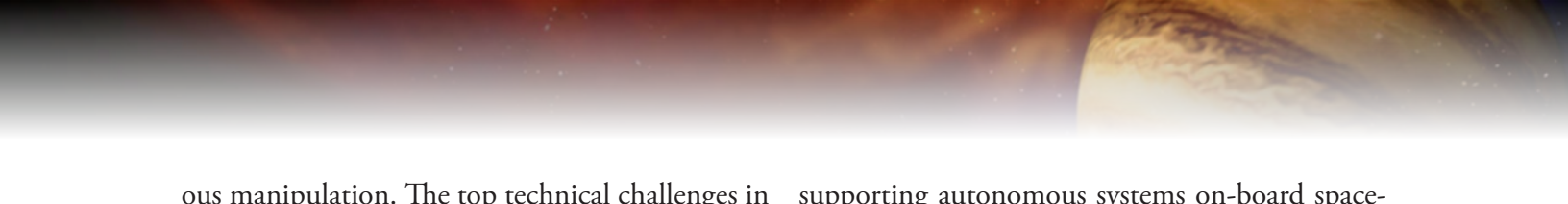
The RTA Roadmap effort has focused on the classical areas of sensing & perception, mobility, manipulation, human-systems interfaces, autonomous rendezvous and docking, and system autonomy. An additional sub-topic was added for RTA-specific systems engineering such as human safety in proximity to robots. Functional capabilities were identified within each of these sub-topics where advances in processors, communication, batteries and materials have enabled major leaps forward in the past decade. Sensing and perception research seeks new detectors, instruments and techniques for localization, proprioception, obstacle detection, object recognition and the processing of that data into a system's perception of itself and its environment. Mobility research includes surface, subsurface, aerial and in-space locomotion, from small machines to large pressurized systems that can carry crew for long excursions, using modes of transport that include flying, walking, climbing, rolling, tunneling and thrusting. Contemporary manipulation research is focused on force control, compliance, eye-hand coordination, tactile control, dexterous manipulation, grasping, multi-arm control and tool use. Autonomous systems research seeks to improve performance with a reduced burden on crew and ground support personnel, achieving safe and efficient control, and enabling decisions in complex and dynamic environments. RTA human-systems interface research includes classical areas of tele-robotics such as haptics, human-systems interfaces, and augmented reality with newer topics that include human safety, human-robot teams, crew decision support, interaction with the public, and supervision across the time delays of space. Automated rendezvous and docking research has focused on coupled sensing and range measurement systems for vehicle pose estimation across short and long ranges relative navigation sensors for various constraints, autonomous GN&C algorithms and implementation in flight software, integrations and standardization of capabilities,, docking mechanisms that mitigate impact loads that can increase allowable spacecraft mass, electrical/fluid/atmospheric transfer across docked interfaces. Systems engineering topics identified for the RTA domain include the required tolerance to environmental factors of vacuum, radiation, temperature, dust, and system level modular design philosophies that provide for interoperability and support international standards. Interfaces will exist between the RTA domain and other roadmap domains, including power, destination systems, and information/modeling/simulation, habitation, and communications technology.

Sensing and Perception metrics include resolution, accuracy, range, tolerance of environmental conditions, and power. Mobility system metrics include range, payload, speed, life and mass. Manipulation system metrics include strength, reach, mass, power, resolution, minimum force/position, and number of interfaces handled. Human systems interface metrics include efficiency indices such as mean time for a human to intervene in a system. Autonomous system metrics include number of humans per system, mean time between human interventions, and number of functions performed per intervention. Autonomous rendezvous and docking metrics include near and far range, resolution, accuracy, mean docking impact impulse, mean docking alignment error at contact, and capture envelope.

The roadmap (see Figure R) evaluates dozens of NASA missions of the four Mission Directorates over the next few decades and maps technology push and pull elements from the RTA core disciplines into those missions, identifying ~100 individual technologies that are enabling or strongly enhancing for those missions.

The top technical challenges for sensing and perception are object recognition and pose estimation and fusing visual, tactile and force sensors for manipulation. The top technical challenges for mobility are achieving human-like performance for piloting vehicles and access to extreme terrain in zero, micro and reduced gravity. The top technical challenges for manipulation are grappling and anchoring to asteroids and non-cooperating objects and exceeding human-like dexter-

ous manipulation. The top technical challenges in human-robot interfaces are full immersion telepresence with haptic, multi sensor feedback, understanding and expressing intent between humans and robots, and supervised autonomy of dynamic/contact tasks across time delay. The top technical challenge in Autonomy is verification of autonomous systems. The top technical challenge for autonomous rendezvous and docking is proximity operations culminating in its successful accomplishment despite the expected extreme conditions of harsh lighting, unknown near-Earth asteroid gravity and other unknown environmental conditions like dust.

The benefits to NASA of RTA technology include extending exploration reach beyond human spaceflight limitations, reduced risks and cost in human spaceflight, enabling science, exploration and operation mission performance, increasing capabilities for robotic missions, use of robots and autonomy as a force multiplier (e.g. multiple robots per human operator), and autonomy and safety for surface landing and flying UAV's. The benefits outside NASA include bringing manufacturing back to America; electric vehicles, wind turbine control, smart grids, and other green technology; synergy with other government agency robotics programs; in orbit strategic asset inspection, repair and upgrade; automated mining and agriculture; prosthetics, rehabilitation, surgery, tele-surgery, assistive robotics; undersea robotics for exploration and servicing; educational robotics for stimulating Science, Technology, Engineering and Mathematics inspiration; household robotics and automation; emergency response, hazardous materials, bomb disposal; and automated transportation via land, air, and sea.

In summary, NASA's four Mission Directorates are depending on Robotics, Tele-Robotics and Autonomy Technology. Over the next few decades, this technology should aim to exceed human performance in sensing, piloting, driving, manipulating, rendezvous and docking. This technology should target cooperative and safe human interfaces to form human-robot teams. Autonomy should make human crews independent from Earth and robotic missions more capable.

1. GENERAL OVERVIEW

1.1. Technical Approach

Ongoing human missions to the International Space Station have an integrated mix of crew working with IVA and EVA robots teamed with supporting autonomous systems on-board spacecraft and in mission control. Future exploration missions will further expand these human-robot partnerships. Unmanned science missions are exclusively robotic in flight, but are integrated with Earth based science and operations teams connected around the globe. Autonomous unmanned aircraft used in military operations are now seeing civilian and science applications, and the line between piloted aircraft cockpits and tele-robotic command consoles continues to blur. Robots, tele-robots and autonomous systems are already at work in all of NASA's Mission Directorates. NASA will see even more pervasive use of these systems in its future.

The RTA Roadmap effort has focused on the classical areas of sensing & perception, mobility, manipulation, rendezvous & docking, human-systems interfaces, autonomous rendezvous and docking, and system autonomy. An additional sub-topic was added for RTA systems engineering. Specific functional capabilities were identified within each of these sub-topics where advances in processors, communication, batteries and materials have enabled major leaps forward in the past decade. Sensing and perception research seeks new detectors, instruments and techniques for localization, proprioception, obstacle detection, object recognition and the processing of that data into a system's perception of itself and its environment. Mobility research includes surface, subsurface, aerial and in-space locomotion, from small machines to large pressurized systems that can carry crew for long excursions, using modes of transport that include flying, walking, climbing, rolling, tunneling and thrusting. Contemporary manipulation research is focused on force control, compliance, eye-hand coordination, tactile control, dexterous manipulation, grasping, multi-arm control and tool use. Autonomous systems research seeks to improve performance with a reduced burden on crew and ground support personnel, achieving safe and efficient control, and enabling decisions in complex and dynamic environments. RTA human-systems interface research includes classical areas of tele-robotics such as haptics and augmented reality with newer topics that include human safety, human-robot teams, crew decision support, interaction with the public, and supervision across the time delays of space. Automated rendezvous and docking research has focused on coupled sensing and range measurement systems for vehicle pose estimation across short and long ranges, relative navigation sensors for vari-

Figure R: *Robotics, Tele-Robotics and Autonomous Systems Technology Area Strategic Roadmap (TASR)*
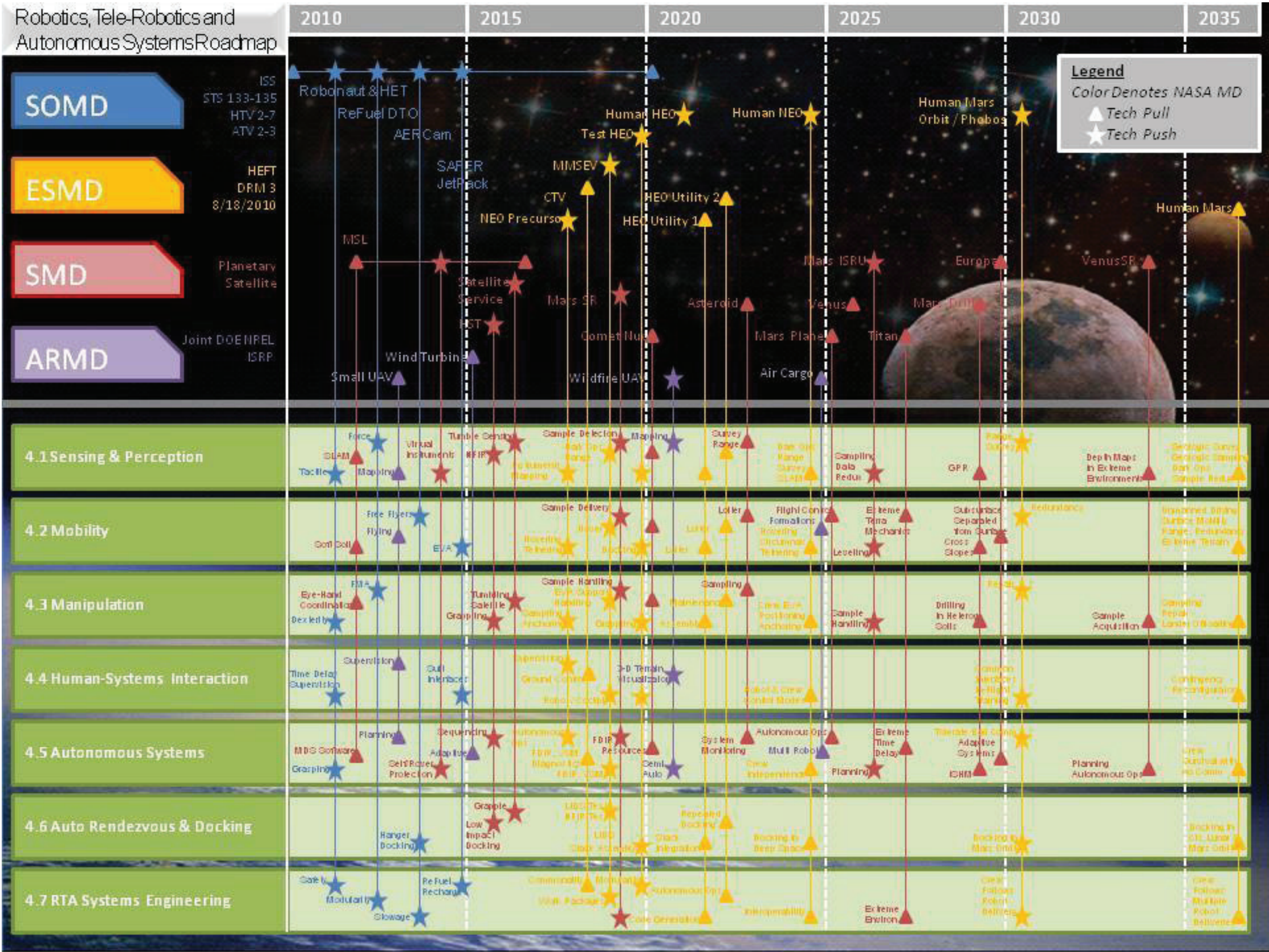
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ous constraints, autonomous GN&C algorithms and implementation in flight software, integration and standardization of capabilities, docking mechanisms that mitigate impact loads that can increase allowable spacecraft structure and mass, electrical/fluid/atmospheric transfer across docked interfaces. Systems engineering topics identified for the RTA domain include the required tolerance to environmental factors of vacuum, radiation, temperature, dust, and system level modular design philosophies that provide for interoperability and support international standards. Interfaces will exist between the RTA domain and other roadmap domains, including power, destination systems, and information/modeling/simulation, habitation, and communications technology.

1.2. Benefits

Spaceflight is costly across the development, flight unit production, launch and operation phases of missions. Spaceflight is also risky to both man and machine. Each of the RTA subtopics is focused on research to reduce cost and risk. An even greater benefit is when new technologies increase capabilities, or add whole new functions that truly "change the game".

So for each subtopic within the RTA domain we seek to make spaceflight safer and more economical, while looking for improvements and breakthroughs as measured with quantifiable metrics. Sensing and Perception metrics include resolution, accuracy, range, tolerance of environmental conditions, and power. Mobility system metrics include range, payload, speed, life and mass. Manipulation system metrics include strength, reach, mass, power, resolution, minimum force/position, and number of interfaces handled. Human systems interface metrics include efficiency indicies such as mean time to intervene in a system. Autonomous system metrics include number of humans per system, mean time between intervention by humans, and number of functions performed per intervention. Autonomous rendezvous and docking metrics include near and far range, resolution, accuracy, mean docking impact impulse, mean docking alignment error at contact, capture envelope.

1.3. Traceability to NASA Strategic Goals

Robotics, Tele-Robotics and Autonomous Systems are prominently mentioned in the US Space Policy released June 28, 2010 (see Figure 1). One of its goals is to "Pursue human and robotic initiatives" to develop innovative technologies (page 4). In the US Space Policy, NASA is directed to

Figure 1. *Cover of the National Space Policy of the United States of America*

"Maintain a sustained robotic presence" in the solar system to conduct science, demonstrate technologies and scout locations for future human missions (page 11).

The Policy also establishes the use of space nuclear power systems to safely enable or significantly enhance space exploration and operational capabilties. The use of nuclear electric and nuclear thermal power will require a significant improvement in autonomous system functions for the management of nuclear power sources providing electrical power, thermal power, and propoulsion. The maturation of autonomous systems will require demonstration missions in interplanetary space. This policy directly drives the need for immediate and sustained development and maturation of autonomous system technologies.

1.4. Technology Push

Robotics, Tele-Robotics and Autonomous Systems represent an exploding domain of research with broad investments beyond NASA and the US. This roadmap seeks to identify technologies that can be integrated for flight missions over the next 25 years. The conventional approach to road mapping involves technology pull, where mission needs are used to guide technology investment and development. The following sections use this approach, identifying missions over the next 25 years and proposing technology needs. At the same time the panel recognized the need for technology push, where major breakthroughs enable new missions or potentially change missions planning with new capabilities. Therefore some investment in basic research is encouraged to invent and mature new approaches that are not today seen as credible.

2. DETAILED PORTFOLIO DISCUSSION

2.1. Technical Area Breakdown Structure (TABS) Diagram

The Robotics, Tele-Robotics and Autonomous Systems Technology Area Breakdown Structure (TABS) is shown in Figure 2.

2.1.1. Sensing

This area includes sensors and algorithms needed to convert sensor data into representations suitable for decision-making. Traditional spacecraft sensing and perception included position, attitude, and velocity estimation in reference frames centered on solar system bodies, plus sensing spacecraft internal degrees of freedom, such as scan-platform angles. Current and future development will expand this to include position, attitude, and velocity estimation relative to local terrain, plus rich perception of characteristics of local terrain — where "terrain" may include the structure of other spacecraft in the vicinity and dynamic events, such as atmospheric phenomena. Enhanced sensing and perception will broadly impact three areas of capability: autonomous navigation, sampling and manipulation, and interpretation of science data.

In autonomous navigation, 3-D perception has already been central to autonomous navigation of planetary rovers. Current capability focuses on stereoscopic 3-D perception in daylight. Active optical ranging (LIDAR) is commonly used in Earth-based robotic systems and is under development for landing hazard detection in planetary exploration. Progress is necessary in increasing the speed, resolution, and field of regard of such sensors, reducing their size, weight, and power, enabling night operation, and hardening them for flight. Imagery and range data is already in some use for rover and lander position and velocity estimation, though with relatively slow update rates. Real-time, onboard 3-D perception, mapping, and terrain-relative position and velocity estimation capability is also needed for small body proximity operation, balloons and airships, and micro-inspector spacecraft. For surface navigation, sensing and perception must be extended from 3-D per-

4.0 RTA

4.1 Sensing & Perception

4.1.1 Stereo vision using natural and structured lighting
4.1.2 LIDAR in extreme lighting conditions
4.1.3 proximity sensing
4.1.4 Sensing non-geometric terrain properties (loadbearing strength, friction, etc.)
4.1.5 Estimation of terrain mechanical properties
4.1.6 Tactile sensing arrays (normal and tangential force)
4.1.7 Gravity sensors for celestial navigation
4.1.8 Terrain-relative navigation
4.1.9 Real-time self-calibration of hand-eye systems

4.2 Mobility

4.2.1 Simultaneous Localization and mapping
4.2.2 Hazard detection algorithms
4.2.3 Active illumination compatible with both humans and robots
4.2.4 3-D path planning with uncertainty
4.2.5 Long-life, extreme environment mechanisms
4.2.6 Robotic jet backpacks
4.2.7 Smart tethers (e.g. commandable release and re-connection)
4.2.8 Robot swarm task decomposition & assignment
4.2.9 Walking in micro-g

4.3 Manipulation

4.3.1 Motion planning algorithm for high DOF systems
4.3.2 Sensing and control for moves to contact and maintaining stable sliding motion
4.3.3 Lightweight, high strength robot arms
4.3.4 Dexterous manipulation and robot hands
4.3.5 Fusion of force, tactile, and visual sensors for monitoring grasps
4.3.6 Grasp planning algorithms robotic drilling mechanisms
4.3.7 Multi-arm/finger manipulation
4.3.8 Planning with uncertainty

4.4 Human-Systems Int.

4.4.1 Crew decision support systems
4.4.2 Immersive visualization
4.4.3 Distributed collaboration
4.4.4. Multi agent coordination
4.4.5 Haptic displays (normal and tangential force)
4.4.6 Methods for displaying range data to humans in understandable form

4.5 Autonomy

4.5.1 Autonomous spacecraft control systems
4.5.2 Autonomous vehicle health prognostic and diagnostic systems
4.5.3 Autonomous human life support control and monitoring systems
4.5.4 Autonomous Planning and Scheduling of Resources
4.5.5 Autonomous Operations
4.5.6 Integrated Systems Health Management
4.5.7 (Fault Detection, Isolation and Recovery) FDIR and Diagnosis
4.5.8 System Monitoring and Prognosis
4.5.9 Trusted (Verification and Valiation of) Complex Adaptive Systems
4.5.10 Automated Software Generation
4.5.11 Software Reliability
4.5.12 Semi automatic systems

4.6 Autonomous Rendezvous & Docking

4.6.1 Autonomous rendezvous and capture
4.6.2 Low impact and androgenous docking systems and interfaces
4.6.3 Relative navigation Sensors - VNS, RF ranging, Natural Feature Imaging Recognition (NFIR) etc.
4.6.4 Robust AR&D GN&C algorithms and FSW
4.6.5 Onboard Mission Manager
4.6.6 AR&D integration and standardization

4.7 RTA Systems Engineering

4.7.1 Human safety
4.7.2 Refueling interfaces and associated tooling
4.7.3 Modular/serviceable interfaces
4.7.4 High performance, low power onboard computers
4.7.5 Environmental tolerance
4.7.6 Thermal control
4.7.7 Robot-to-suit interfaces
4.7.8 Common human-robot interfaces
4.7.9 Crew self sufficiency

Figure 2. *RTA Technical Area Breakdown Structure (TABS) Diagram*

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ception to estimating other terrain properties pertinent to trafficability analysis, such as softness of soil or depth to the load-bearing surface. Many types of sensors may be relevant to this task, including contact and remote sensors onboard rovers and remote sensors on orbiters.

Sampling generally refers to handling natural materials in scientific exploration; manipulation includes actions needed in sampling and handling man-made objects, including sample containers in scientific exploration and handling a variety of tools and structures during robotic assembly and maintenance. 3-D perception, mapping, and relative motion estimation are also relevant here. Non-geometric terrain property estimation is also relevant to distinguish where and how to sample, as well as where and how to anchor to surfaces in micro-gravity or to steep slopes on large bodies. Additional needs include recognizing known objects, estimating the position and orientation of those objects, and fusing measurements from force-torque, tactical, and visual sensors to execute grasping operations and mating/de-mating of pairs of objects.

Onboard science data analysis is important in at least two broad situations: (1) where large data sets must be searched to find things of interest, and it is impractical to downlink the entire data set to Earth, and (2) where time-sensitive phenomena must be detected before the phenomena end (e.g. eruptions) or the spacecraft moves beyond range of further observation. Success stories already include onboard detection of dust devils and clouds by Mars rovers; future examples could include detecting dynamic events on Earth, comets, or Titan and onboard analysis of large, hyperspectral data sets. Perception tends to be very computationally intensive, so progress in this area will be closely linked to progress in high performance onboard computing.
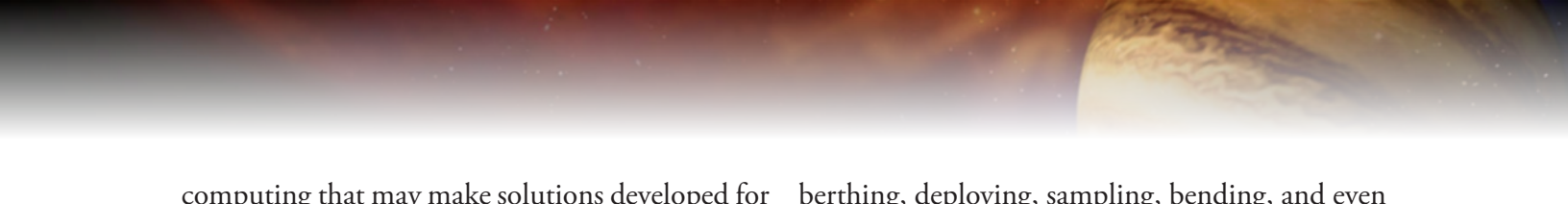
2.1.2. Mobility

The state of the art in robotic space mobility (e.g. not including conventional rocket propulsion) includes the Mars Exploration Rovers and the upcoming Mars Science Laboratory, and for human surface mobility the Apollo lunar roving vehicle used on the final three Apollo missions. Recently, systems have been developed and tested on Earth for mobility on planetary surfaces including the Space Exploration Vehicle and the ATHLETE wheel-on-leg cargo transporter. Both feature active suspension. A series of grand challenges have extended the reach of robotic off-road

mobility to high speeds and progressively more extreme terrain. For microgravity mobility, the Manned Maneuvering Unit (MMU), tested in 1984 and, more recently, the SAFER jet pack provide individual astronauts with the ability to move and maneuver in free space, or in the neighborhood of a Near-Earth Asteroid. The AERCam system flew on STS-87 in 1997 as the first of future small free-flying inspection satellites.

We can expect in the next few decades that robotic vehicles designed for planetary surfaces will approach or even exceed the performance of the best piloted human vehicles on Earth in traversing extreme terrain and reaching sites of interest despite severe terrain challenges. Human drivers have a remarkable ability to perceive terrain hazards at long range and to pilot surface vehicles along dynamic trajectories that seem nearly optimal. Despite the limitations of human sensing and cognition, it is generally observed that experienced drivers can pilot their vehicles at speeds near the limits set by physical law (e.g. frictional coefficients, tipover and other vehicle-terrain kinematic and dynamic failures). This fact is remarkable given the huge computational throughput requirements needed to quickly assess subtle terrain geometric and non-geometric properties (e.g. visually estimating the properties of soft soil) at long range fast enough to maintain speeds near the vehicle limits. This ability is lacking in today's best obstacle detection and hazard avoidance systems.

For free-flying vehicles, either in a microgravity environment or flying through an atmosphere, we can similarly expect that robotic vehicles will become capable of utilizing essentially all available vehicle performance, in terms of acceleration, turn rate, stopping distance, etc. without being limited either by the onboard sensors, computational throughput, or appropriate algorithms in making timely decisions. Future missions may be identified for small or nano satellites, where breakthroughs in miniaturization of electronics, cameras and other sensors will allow functions performed by large spacecraft at less than 1% the mass and cost.

NASA in particular has the need to reach sites of scientific interest (e.g. on the sides of cliffs) that are of less interest to other agencies. So NASA needs to focus especially on those aspects of extreme-terrain surface mobility, free-space mobility and landing/attachment that will not be developed by anyone else. Also, NASA has environmental constraints such as thermal extremes and rad-hard

computing that may make solutions developed for others in-applicable to NASA. While high speed operations are of only limited use to NASA, mission success will often depend on reliable, sustained operations, including the ability to move through the environment long distances without consuming too much of the mission timeline.

Mass, and to some degree power, generally need to have a much greater degree of emphasis in the design process for NASA missions than others. As a result, mobility systems that can "brute force" a solution to a difficult problem may need to be accomplished by "finesse" in a NASA context. A good example of this is the use of tank-treads of high-mobility military vehicles. Such systems provide good mobility but tend to entrain debris into the running gear in a way that requires lots of mass and power to crush and expel. As a result, NASA has invested in alternatives such as multi-wheel vehicles that have similarly low ground pressures but much lower power requirements. This trend of NASA needing to invest in specialized systems that meet its own unique needs will presumably continue. A mobility system is highly dependent on its power subsystems, especially for long transit, working against friction, or when carrying heavy payloads. In particular the specific power and specific energy metrics will dominate a mobility system's range, speed and payload capacity. Technology Area 3 addresses new technologies for improved space power and energy storage systems.

Other agencies have made significant development and investment in Unmanned Aerial Vehicles (UAVs). These capabilities can be adapted and applied to exploration of planetary surfaces and weather. In particular, NASA will need to develop fully autonomous and automated UAVs for operations on distant planets. Coordination of multiple robotic systems is an active area of research. Combinations of heterogeneous systems, such as flying and roving systems is potentially useful for surface missions, pairing long range sensing on the flyer with higher resolution surface sensing on the rover.

Mobility applications for human missions are described in Technical Area 7, Human Exploration Destinations Systems. These include rovers, hoppers, docking spacecraft and EVA mobility aids such as exoskeletons and jetpacks.

2.1.3. Manipulation Technology

Manipulation is defined as making an intentional change in the environment. Positioning sensors, handling objects, digging, assembling, grappling, berthing, deploying, sampling, bending, and even positioning the crew on the end of long arms are tasks considered to be forms of manipulation (see Figure 3). Arms, cables, fingers, scoops, and combinations of multiple limbs are embodiments of manipulators. Here we look ahead to missions' requirements and chart the evolution of these capabilities that will be needed for space missions. Manipulation applications for human missions can be found in Technology Area 7 as powered exoskeletons, or payload offloading devices that exceed human strength alone.

Sample Handling- The state of the art is found in the MSL arm, Phoenix arm, MER arm, Sojourner arm, and Viking. Future needs include handling segmented samples (cores, rocks) rather than scoop full of soil, loading samples into onboard devices, loading samples into containers, sorting samples, and cutting samples.

Grappling- The state of the art is found in the SRMS, MFD, ETS-VII, SSRMS, Orbital Express, and SPDM. Near term advances will be seen in the NASA Robonaut 2 mission. Challenges that will need to be overcome include grappling with a dead spacecraft, grappling a natural object like an asteroid, grappling in deep space, and assembly of a multi-stack spacecraft.

Eye-Hand Coordination- The state of the art is placement of MER instruments on rocks, Orbital Express refueling, SPDM ORU handling and Phoenix digging. Challenges to be overcome include working with natural objects in micro gravity (asteroids), operation in poor lighting, calibration methods, and combination of vision and touch.

EVA positioning- The EVA community has come to rely on the use of large robot foot restraints versus having crew climb. The state of the art is found in the SRMS and SSRMS. These arms were originally designed for handling inert payloads, and no controls were developed for control by the crew on the arm. Challenges to be overcome involve letting crew position themselves without multiple IV crew helping, safety issues, and operation of these arms far from Earth support.

Assembly and Servicing - The state of the art is in only large scale assembly of spacecraft modules with the SRMS and SSRMS, and servicing is limited to ORU handling with Orbital Express and SPDM. Challenges to be overcome include opening and closing boxes, handling flexible materials, force controlled mating of structure, mating electrical and fluid connectors, fastening, rout-

Figure 3. *Orbital Express, Phoenix Arm, MSL Arm, Robonaut 2, SSRMS & SPDM, JAXA MFD, ETS-VII*

ing cables and hoses, tether/capture management, cutting and bending, and working with EVA interfaces.

Tool Use - The state of the art in space tool use is found in the Sojourner and MER instruments. Near term advances will be seen with the Mars Science Lab and uses of the SPDM RMCT tool on ISS. Challenges to be overcome include use of a minimum set of tools, common too interfaces, common robot-EVA-tools, robot dexterity to handle tools built for humans, and smart tools that go beyond mechanical pass throughs.

2.1.4. Human-Systems Interfaces

The ultimate efficacy of space systems depends greatly upon the interfaces that humans use to operate them. The current state of the art in human-system interfaces is summarized below along with some of the advances that are expected in the next 25 years.

Human operation of most systems today is accomplished in a simple pattern reminiscent of the classic "Sense – Plan – Act" control paradigm for robotics and remotely operated systems. The human observes the state of the system and its environment, forms a mental plan for its future action, and then commands the robot or machine to execute that plan. Most of the recent work in this field is focused on providing tools to more effectively communicate state to the human and capture commands for the robot, each of which is discussed in more detail below.

Current human-system interfaces typically include software applications that communicate internal system state via abstract gauges and readouts reminiscent of aircraft cockpits or overlays on realistic illustrations of the physical plant and its components. Information from sensors is available in its native form (for instance, a single image from a camera) and aggregated into a navigable model of the environment that may contain data from multiple measurements and sensors. Some interfaces are adapted to immersive displays, mobile devices, or allow multiple distributed operators to monitor the remote system simultaneously.

Future interfaces will communicate state through increased use of immersive displays, cre-ating "Holodeck"-like virtual environments that can be naturally explored by the human operator with "Avatar"-like telepresence. These interfaces will also more fully engage the aural and tactile senses of the human to communicate more information about the state of the robot and its surroundings. As robots grow increasingly autonomous, improved techniques for communicating the "mental state" of robots will be introduced, as well as mechanisms for understanding the dynamic state of reconfigurable robots and complex sensor data from swarms.

Current human-robot interfaces typically allow for two types of commands. The first are simple, brief directives, sometimes sent via specialized control devices such as joysticks, which interrupt existing commands and immediately affect the state of the robot. A few interfaces allow the issuance of these commands through speech and gestures. These immediate commands are ineffective when significant communications delay is present. The second are higher-level goals, frequently presented in a sequence, that engage autonomous behaviors on the robot and require a significant amount of time to complete. Interfaces that allow the latter type of commanding offer modeling and simulation capabilities that attempt to predict the outcome of a series of commands.

Future interfaces will make use of the steady advances in mobile devices and the entertainment industry to provide more intuitive and natural robot command devices. Robots will also be able to more accurately interpret human speech and gestures in the absence of these devices, enabling robots to more effectively work with humans. In many cases, commands will be automatically generated based on observations of the human's natural interactions with a virtual or real environment, removing the need for the human to explicitly issue commands at all.

Additional progress in two crosscutting areas is necessary to enable the advances described above. First, the lack of developed standards and conventions for the control of robotic systems is having a negative impact on usability and limits the leveraging of one robot's interface for another. Second, as humans interact more closely with robotic sys-

tems (in some cases riding inside them), increased focus on the need for safe physical interactions between robots and humans is necessary.

While human-machine interfaces are complex, the interfaces between multiple machines should be more easily defined and consistent. This will be of importance when humans are working with multiple machines. The complete research domain includes combinations of "n" humans paired with "m" machines.

2.1.5. Autonomy

Autonomy, in the context of a system (robotic, spacecraft, or aircraft), is the capability for the system to operate independently from external control. For NASA missions there is a spectrum of Autonomy in a system from basic automation (mechanistic execution of action or response to stimuli) through to fully autonomous systems able to act independently in dynamic and uncertain environments.

Two application areas of autonomy are: (i) increased use of autonomy to enable an independent acting system, and (ii) automation as an augmentation of human operation. Autonomy's fundamental benefits are; increasing a system operations capability, cost savings via increased human labor efficiencies and reduced needs, and increased mission assurance or robustness to uncertain environments.

An "autonomous system" is defined as a system that resolves choices on its own. The goals the system is trying to accomplish are provided by another entity; thus, the system is autonomous from the entity on whose behalf the goals are being achieved. The decision-making processes may in fact be simple, but the choices are made locally. In contrast, an "automated system" follows a script, albeit a potentially quite sophisticated one; if it encounters an unplanned-for situation, it stops and waits for human help, e.g. "phones home". The choices have either been made already, and encoded in some way, or will be made externally to the system

Key attributes of such autonomy for a robotic system include the ability for complex decision making, including autonomous mission execution and planning, the ability to self-adapt as the environment in which the system is operating changes, and the ability to understand system state and react accordingly. Variable (or mixed initiative) autonomy refers to systems in which a user can specify the degree of autonomous control that the system is allowed to take on, and in which this de-

gree of autonomy can be varied from essentially none to near or complete autonomy. For example, in a human-robot system with mixed initiative, the operator may switch levels of autonomy onboard the robot. Controlling levels of autonomy is tantamount to controlling bounds on the robot's authority, response, and operational capabilities.

The Mars Exploration Rovers are the state-of-the-practice for operational mixed initiative autonomy in a space robotic system. Multi-day top-level plans of rover actions are developed on the Earth for execution on-board the Rovers. On-board autonomy enables hazard avoidance while driving, provides limited on-board automation of the acquisition of science data, and provides limited failure mode behaviors and actions when faults occur in the system.

Variable levels of autonomous systems can be applied to virtually any NASA system: aircraft (autonomous, remotely-piloted, commercial free-flight systems); spacecraft (robotic systems performing exploration, crewed spacecraft with decision support systems); and ground-based automation to support science discovery, vehicle system management, and mission operations. Greater use of highly adaptable and variable autonomous systems and processes can provide significant time-domain operational advantages to robotic systems or crewed systems that are limited to human planning, decision, and data management speeds. Crew centered operations is a complex challenge because it means that the crew must be able to track and modify daily activity plans, monitor key systems, isolate anomalies, and select and perform any required recovery procedures. All this requires significant on-board automation and system autonomy to support the crew.

Achieving these gains from use of autonomous systems will require developing new methods to establish "trusted autonomy" through verification and validation (V&V) of the near-infinite state systems that result from high levels of adaptability; state management and system diagnostic/prognostic technologies to enable complex systems to operate across a range of functional capabilities; and for human decision support systems that manage multivariate plans and constraint optimizations.

Autonomous fault detection, isolation, and recovery are critical for overall system autonomy. These real-time health management functions require assessments and decisions in a timeframe of milliseconds to minutes. Representative capabilities include crew escape and abort decisions as

well as on-board diagnostics and recovery.

Autonomous systems research involves the integration and implementation of several advanced autonomy techniques. Autonomous systems require unambiguous knowledge of the vehicle states, including location of failures and future states. ISHM provides the state determination, diagnostics, and prognostics of the systems and vehicle. Buidling upon this state information, on-board mission executive and mission planning autonomoy provides the decision making necessary to manage the mission, vehicle, and failure responses. Radiation hardened, high performance processors are essential to enable this level of functionality (see TA 11 for more detail on processing). Different autonomous algorithms may prove to perform different functions better and different vehicle systems (i.e., life support, propulsion, thermal control, electrical power) may require different algorithmic approaches. The integration of different algorithms to provide a consistent management function has not yet been accomplished. Verification and Validation of non-deterministic algorithms (e.g., dynamic neural networks, inference engines, fuzzy logic) will require new methods in order to verify and validate the safe operation of these algorithms in all possible vehicle conditions.

With crew sizes of perhaps 4 – 6, the availability of crew is limited to perhaps 2 crew members managing the entire vehicle at any given time. Some believe that the level of complexity of an interplanetary spacecraft will be similar to that of a nuclear attack submarine which has 134 crew. Managing a vehicle of this complexity with only 2 crew members will require significant automation of the vehicle management functions. In addition, as the vehicle moves beyond 5 light minutes from Earth, response time becomes a limiting factor. The vehicle will have to respond to unexpected conditions such as solar flares or system failures without input from terrestrial control centers or operators. Autonomous and automated operation for this level of complexity and crew size has not been demonstrated nor fully understood.

2.1.6. AR&D[1]

The ability of space assets to autonomously rendezvous and dock enables human and science exploration, as well as satellite servicing/rescue, and is an essential capability for the future of human and robotic missions. However, NASA and the U.S. space industry have yet to develop and demonstrate a robust Automated/Autonomous Rendezvous and Docking (AR&D) capability suite that can be confidently utilized on human spaceflight and robotic vehicles over a variety of design reference missions. While Space Shuttle rendezvous activities have been 100% successful, they have been limited to LEO operations and relied heavily on ground operators and flight crew to increase robustness and probability of mission success. Operational ISS transport and re-supply is currently provided by AR&D systems in the form of ATV, HTV, and Progress, and in the future, by US commercial vendors. These systems are optimized to take advantage of LEO infrastructure, such as GPS, and ground controllers, and are therefore not extensible to the different mission classes beyond LEO without significant NRE. Other recent AR&D technology demonstrators such as Orbital Express and XSS-11 have flown successful or partially successful Rendezvous, Proximity Operations, and Docking (RPOD) missions with some limited human involvement from ground controllers. However, much of the hardware demonstrated on these missions is no longer available to support future flights. Since full autonomy and automation has not been required for rendezvous and docking missions as yet, NASA does not have a ready-to-fly AR&D capability that would be considered routine, reliable, versatile, and cost-effective, especially for missions beyond Low Earth Orbit (LEO).

AR&D is a capability requiring many vehicle subsystems to operate in concert. It is important to clarify that AR&D is not a system and cannot be purchased off the shelf. This strategy focuses on development of a certified, standardized capability suite of subsystems enabling AR&D for different mission classes and needs (see Figure 4). This suite will be incrementally developed, tested and integrated over a span of several missions. This technology roadmap focuses on four specific subsystems required for any AR&D mission.

1) *Relative Navigation Sensors* – During the course of RPOD, varying accuracies of bearing, range, and relative attitude are needed for AR&D. Current implementations for optical, laser, and RF systems are mid-TRL (Technology Readiness Level) and require some development and flight experience to gain reliability and operational confidence. Inclusion of the ability

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[1]   Summary from "A Strategy for the U.S. to Develop and Maintain a Versatile Mainstream Capability for Automated/Autonomous Rendezvous and Docking in Low Earth Orbit and Beyond", Draft August 2010, Authored by the AR&D Community of Practice, a collaboration among ARC, DFRC, GRC, GSFC, HQ, JSC, JPL, LaRC, MSFC, NESC, and the HQ Office of the Chief Engineer.

for cooperating AR&D pairs to communicate directly can greatly improve the responsiveness and robustness of the system.

2) *Robust AR&D GN&C Real-Time Flight Software (FSW)* – AR&D GN&C algorithms are maturing, however, implementing these algorithms into FSW is an enormous challenge. A best practice based implementation of automated/autonomous GN&C algorithms into real-time FSW operating systems needs to be developed and tested.

3) *Docking/Capture* – NASA is planning for the imminent construction of a new low-impact docking mechanism built to an international standard for human spaceflight missions to ISS. A smaller common docking system for robotic spacecraft is also needed to enable robotic spacecraft AR&D within the capture envelopes of these systems. Assembly of the large vehicles and stages used for beyond LEO exploration missions will require new mechanisms with new capture envelopes beyond any docking system currently used or in development. Development and testing of autonomous robotic capture of non-cooperative target vehicles in which the target does not have capture aids such as grapple fixtures or docking mechanisms is needed to support satellite servicing/rescue.

4) *Mission/System Managers* – A scalable spacecraft software executive that can be tailored for various mission applications, for the whole vehicle, and various levels of autonomy and automation is needed to ensure safety and operational confidence in AR&D software execution. Numerous spacecraft software executives have been developed, but the necessary piece that is missing is an Agency-wide open standard which will minimize the costs of such architectures and its ability to evolve over time to help overcome general fears about autonomy/automation.

Although none of the subsystems are low TRL, some are not mature enough to be considered routine and cost-effective, and all need some level of development, ground testing and/or on-orbit demonstration as well as incorporation of lessons learned through integration with other subsystems on a variety of spacecraft before they can all be considered part of a versatile mainstream U.S. capability. By evaluating mission characteristics against mission class, the above figure illustrates the essential nature of AR&D as an enabler of NASA missions over the next 20-25 years. The main challenges of AR&D are a) the integration of subsystems to form a robust, cohesive, autonomous system and b) standardization of AR&D suites between vehicles that operate in the same theater so that vehicles built by different Programs/projects can interoperate. The Advanced Video Guidance System (AVGS) represents NASAs current AR&D capability. The system has successfully completed test flights on the Shuttle, the Demonstration of Autonomous Rendezvous Technologies (DART), and Orbital Express (OE-1). This capability employs the use of reflectors on the target spacecraft and provides for safe docking and mating operations.

While landing on planetary bodies is the domain of TA9 (Entry, Descent and Landing Systems) there may be some overlap with Autonomous Rendezvous and Docking when the planetary body is small, as in the case of an asteroid. For very small objects the gravity forces approach zero and the landing approaches docking. Measuring spin rate, matching rates and the use of anchoring devices will likely have much in common with the previously described technologies. Additional challenges will arise with a dusty and heterogeneous landing surface.

2.1.7. RTA Systems Engineering

Many advances in robotics and autonomy depend on increased computational power. Therefore, advances in high performance, low power

	Crewed Missions				Robotic or Astronaut-Assisted Robotic Missions				
	ISS Supply	Crew Return LEO/BEO	On-Orbit Assembly		Servicing	Sample Return	Rescue	Small-Body Proximity Ops	
Characteristics of Foundational Missions									**Characteristics of Advanced (More Difficult) Missions**
Automated									Automated & Autonomous
Target Cooperative									Non-cooperative
Target Geometry Known									Target Geometry Unknown
Target Attitude Fixed									Target Attitude Tumbling
Far-Rendez Rel Nav by Ground									Far-Rendez Rel Nav On-Board
# of vehicles =2									# of vehicles >2
AR&D duration long									AR&D duration short

Figure 4. *Notional AR&D Capabilities vs. Mission Class and Order of Difficulty*

onboard computers are central to more capable space robotics. Current efforts in this direction include exploiting high performance field programmable gate arrays (FPGAs), multi-core processors, and enabling use in space of commercial grade computer components through shielding, hardware redundancy, and fault tolerant software design. Further pushes in these or other directions to achieve greater in-space computing power are needed.

Modular interfaces are needed to enable tool change-out for arms on rovers and for in-space robotics assembly and servicing. When robots and humans need to work in close proximity; sensing, planning, and autonomous control system for the robots, and overall operational procedures for robots and humans, will have to be designed to ensure human safety around robots.

Developing modular robotic interfaces will also allow multiple robots to operate together. These modular interfaces will allow structural, mechanical, electrical, data, fluid, pneumatic and other interaction. Tools and end effectors can also be developed in a modular manner allowing interchangeability and a reduced logistics footprint. Modular interfaces will be the building block for modular self-replicating robots, and self-assembling robotic systems.

Reconfigurable system design offers the ability to reconfigure mechanical, electrical and computing assets in response to system failures. Reconfigurable computing offers the ability to internally reconfigure in response to chip level failures caused by environmental (i.e. space radiation), life limitations, or fabrication errors.

System verification will be a new challenge for human rated spacecraft bound for deep space. New V&V approaches and techniques will be required, and in-flight re-verification following a repair may be necessary.

2.2. Subtopics and Mission Diagram

The subtopics and mission diagram is shown in the Figure R foldout.

2.3. Mission by Mission Assessment

2.3.1. SOMD Missions

2.3.1.1. Robonaut 2 mission to ISS

During FY11 the Robonaut 2 system (see Figure 5) will be launched on STS-133 and delivered to the ISS in what will become the Permanent Multipurpose Module (PMM). Robonaut 2 (R2) is the latest in a series of dexterous robots built by NASA as technology demonstration, now
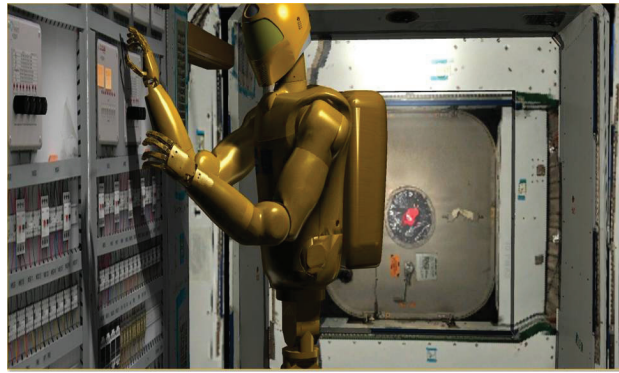

Figure 5. *Robonaut 2 concept for working inside ISS*

evolving from Earth to in-space experiments. The main objectives are to explore dexterous manipulation in zero gravity, test human-robot safety systems, test remote supervision techniques for operation across time delays, and experiment with ISS equipment to begin offloading crew of housekeeping and other chores. The R2 was built in a partnership with General Motors, with a shared vision of a capable but safe robot working near people.

The R2 has the state of the art in tactile sensing and perception, as well as depth map sensors, stereo vision, and force sensing. The R2 will be deployed initially on a fixed pedestal with zero mobility, but future upgrades are planned to allow it to climb and reposition itself at different worksites. Robonaut 2's dexterous manipulators are the state of the art, with three levels of force sensing for safety, high strength to weight ratios, compliant and back drivable drive trains, soft and smooth coverings, fine force and position control, dual arm coordination, and kinematic redundancy. Human interfaces for the R2 include direct force interaction where humans can manually position the limbs, trajectory design software tools, and script engines. R2 is designed to be directly tele-operated, remotely supervised, or run in an automated manner. The modular design can be upgraded over time to extend the Robonaut capabilities with new limbs, backpacks, sensors and software.

2.3.1.2. ISS Refueling

The Robotic Refueling Dexterous Demonstration (R2D2) is a multifaceted payload designed for representative tasks required to robotically refuel a spacecraft. Once mounted to the International Space Station, the demonstration will utilize the R2D2 payload complement, the Special Purpose Dexterous Manipulator (SPDM) robotic arms, and 4 customized, interchangeable tools to simulate the tasks needed to refuel a spacecraft us-

ing its standard ground fill-and-drain valve. During the mission, operators at JSC will maneuver the SPDM robotic arms which will interact with the R2D2 payload box and complete its robotic tasks. Using SPDM's end effector and interchangeable R2D2 tools, operators will locate and access the fuel valve on the R2D2 payload box, uncap it, open the manual valve, and then transfer a liquid, simulated fuel through the tool interface into the fill-and-drain valve. A "busy board" on the R2D2 payload box will support the demonstration of general robotic operations relevant to space servicing. Four advanced tools were developed for this mission. Each tool is equipped with two integral cameras to help operators guide their maneuvers. The cameras use the OTCM umbilical connector for power and data.

2.3.1.3. Free-flyer Inspection Robot

This proposed technology push mission is based on an ISS utilization proposal titled "ISS Free flyer for Inspection, Remote Viewing, Science and Technology". The small free-flyer would be taken to ISS and flown outside through the JAXA airlock, then back inside for refurbishment. The design is based on a mix of results from the AERCam flight DTO (STS-87), as well as technology work done for Mini-AERCam (JSC) (see Figure 6), Inspector (JPL), PSA (MIT,ARC) and other free flyer work in universities and other agencies. The free-flyer benefits both current human spaceflight (ISS) and future exploration missions. In near-term operational applications, an external free flyer provides beneficial views of on-orbit maintenance and servicing tasks that cannot be obtained from fixed cameras, cameras on robotic manipulators, or cameras carried by crewmembers during EVA. Similar tasks are anticipated for exploration missions: Inspect descent vehicle thermal protection system before entry and landing; provide alternative to EVA inspection during lunar cruise or interplanetary flight; provide visual inspection cues to aid in developing repair plans and procedures for EVA tasks, including in-space assembly and maintenance.

The free-flyer represents the state of the art in remote sensing instruments, with a 10x reduction in mass and power due to the small scale of the system (<20Kg). The mobility requires complete 6 axis motion control using a cold jet system that can be refueled IVA, relative navigation in space, proximity loiter for inspection, obstacle avoidance and trajectory planning. Human interfaces include direct handling, teleoperation, and remote supervision. Autonomous skills for hover, relative trajectories, and autonomous rendezvous and docking with the JAXA airlock are required to retrieve the free-flyer.

2.3.1.4. Astronaut JetPack

As humans extend their reach to asteroids or other in-space destinations, the ability to fly will become essential for human mobility and locomotion. The ISS is designed with handrails and tether points to assist EVA, but asteroids and satellites have no such features. EVA for the Shuttle and ISS missions relies on the SAFER Jetpack (see Figure 7) for emergency recovery if an astronaut falls off the spacecraft, but the SAFER is single string, and can only be used if the astronaut looses grip and a tether system fails. This technology push mission would develop a multi-string Jetpack able to be used for nominal flight during EVA on ISS, as well be applied to asteroid and high orbit missions where handrails and tether points are not available.

Sensing and perception requirements are minimal,

Figure 6. *Mini AERCam Image and Top Level Assembly*

Figure 7. *Existing Simplified Aid for EVA Rescue (SAFER) Jetpack*

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though the jetpack could be augmented with future sensor payloads for specific missions. The mobility system is complete 6 axis motion control, with >10 m/s delta V for the combined mass of the crew, suit and jetpack. The base jetpack would have no manipulation, but be modular so that future upgrades are possible. The human interface will provide suit interaction, as well as access to pre recorded waypoints and system data/status. The nominal mode of control will be by the crew member wearing the Jetpack, but remote control will be possible to rescue injured crew. Rendezvous and docking will allow the crew member to return to airlocks, suit ports and worksites with an in-space version of cruise control.

2.3.1.5. ISS DPP

The Dexterous Pointing Payload (DPP) is a demonstration payload that will be installed and subsequently exercised on the ISS. In preparation for servicing missions requiring greater dexterity and tracking capability, the DPP will demonstrate the algorithms and control mechanisms to locate and point at a specific location on Earth or a celestial object. DPP performs attitude determination using a star tracker and an Inertial Measurement Unit (IMU). It will receive target parameters via commands from a ground terminal, and will send rate requests to the ISS Robotic Workstation Software (RWS) to achieve desired instrument pointing. This closed-loop control of Dextre (SPDM) enables real-time pointing and disturbance reduction that is beneficial for a wide range of servicing architectures.

2.3.1.6. Geo Fuel

The mission consists of a servicer spacecraft that can sequentially capture and control several legacy, non-cooperative satellites in nearly co-planar geosynchronous orbits, refuel them, or relocate them to a disposal orbit 350 km above the GEO belt. The servicer spacecraft launches into geosynchronous orbit and then executes sorties to multiple customer satellites. At the start of the mission, the customer satellites (near the end of their mission life for refuel; at the end of their life for supersync) are on-orbit waiting for fuel or a boost to a disposal orbit. The servicer spacecraft is equipped with all hardware, algorithms and fuel necessary for supervised autonomous rendezvous and capture (AR&C), and refueling or supersync of the customers. The servicer is launched and inserted directly into GEO in the plane of the first customer satellite. The AR&C sequence puts the servicer onto a safety ellipse about the customer spacecraft

during which time it performs pose estimation to accurately determine its position and attitude relative to the customer. The servicer then executes a series of maneuvers to acquire and translate down a capture axis, maneuvers the robotic arms to within approximately 1 meter of the customer (placing the arms in a predefined capture box), and finally autonomously grasping the customer. The servicer then refuels the customer or boosts the stack into a super-synchronous orbit (GEO + 350 km) as per NASA-STD-8719.14 (Process for Limiting Orbital Debris). It then releases the customer satellite and waits until the next customer is ready for refuel or removal.

2.3.1.7. HST

The mission launches a deorbit module into low Earth orbit to rendezvous and berth with the Hubble Space Telescope at the end of the life of the observatory and deorbits it. The grappling of HST upon approach would require a closed loop autonomous rendezvous and capture system. After capture, the servicing vehicle would perform a series of maneuvers to deorbit the observatory. However, prior to those maneuvers, the servicer could perform servicing technology demonstrations on a well understood serviceable platform before the deorbit occurs. This would reduce risk of future robotic servicing missions in a low risk environment as the telescope is being deorbited anyway.

2.3.2. ESMD Missions

2.3.2.1. Near Earth Asteroid (NEA) Robotic Precursor

At the time of this writing three classes of robotic missions are being proposed as precursors to Near Earth Asteroids. These classes are a survey observa-

Figure 8. *Near Earth Asteroid Rendezvous (NEAR) mission to Eros 1996-2001*

tory in space, a rendezvous mission that does not land on the asteroid, and a robotic mission to explore the asteroid's surface. NASA's Wide-field Infrared Survey Explorer (WISE) has observed over 100,000 asteroids, only 90 of which are in the near Earth class, leaving uncertainty that a survey mission can better resolve. A robotic rendezvous with a NEA will position sensors closer to the surface to collect better images, record spin rate, measure magnetic properties, and build a complete 3D surface map. Robotic missions that contact an asteroid's surface will be coupled with standoff imaging, providing the same data as the rendezvous mission but with additional surface data and the ability to study dust/rock ejecta. These missions are unlikely to be before 2015.

The survey mission has little requirement for Robotics, Tele-robotics and Autonomy beyond contemporary spacecraft engineering. The rendezvous mission would benefit from new mapping sensors and can be used as a test demonstration of autonomous rendezvous algorithms and sensors at mid-range.

Relative navigation sensors, GN&C algorithms, and mission manager subsystems can be integrated and demonstrated. An asteroid contact mission that includes controlled landing and sampling, and perhaps anchoring will challenge sensing (depth maps, materials), perception (map sensor fusion), mobility (landing), manipulation (anchoring and sampling), autonomy (remote ops), and be a more complete test of rendezvous at mid and near range down to contact.

2.3.2.2. Crew Transfer Vehicle (CTV)

Design Reference Missions (DRM's) produced by the Human Exploration Framework Team (HEFT) identified a need for a Crew Transfer Vehicle (CTV) for ascent and entry capabilities (see Figure 9). This road mapping team studied several of the HEFT DRM's and found roles for either a CTV or commercial capsule in all cases. The CTV is designed to return an exploration crew of up to 4 crew members from an interplanetary trajectory directly to the Earth (water landing). The CTV is based on the Orion crew module design. Active duration is on the order of 36-40 hours. First launch for the CTV varies from 2019 to 2023 across the HEFT DRM's, or never if a commercial capsule option is pursued.

Little or no sensing, perception or manipulation is needed for the CTV. The spacecraft will need to support autonomous rendezvous and docking, where sensor technology will be need-
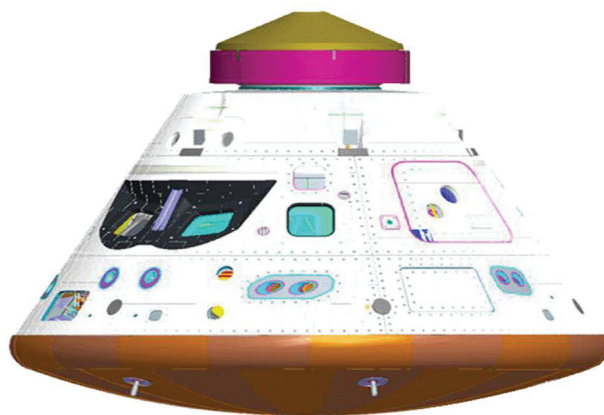

Figure 9. *Concept for a Crew Transfer Vehicle*

ed. If missions choose to grapple the CTV, a manipulator grapple fixture can be added. Human interfaces will be minimal, with launch and entry being highly automated functions. The Crew Transfer Vehicle (CTV) will require onboard autonomous systems in order to achieve the reliability and affordability required by the President and Congress. The CTV will need autonomous systems to manage the spacecraft, requiring ground assistance only when a significant state change has occurred which affects mission success or when a state change has occurred beyond the limits of the onboard systems. Autonomous systems need to be able to minimize the need for operator assistance thereby limiting the size of ground based operations teams and minimizing operations costs. If a strong ground operator dependence is required then the CTV will not be able to be transported beyond the cis-lunar system as crew time will not be available to monitor the vehicle. The CTV will need a modular docking interface that is compatible with the MMSEV and other spacecraft.

2.3.2.3. Multi Mission Space Exploration Vehicle

Designed to compliment capsules used for launch and re entry, the MMSEV (see Figure 10) is designed to provide in-space functions such as EVA support, habitation, and exploration of man-made satellites or asteroids. It will be capable of re-fueling, and could be tested initially with missions to ISS or HEO. The cabin will have commonality with future surface rovers, providing multiple applications and refinement of the technology on a flexible path to Mars. The cabin is design to nominally support 2 crew for 2 weeks, or more crew or duration in contingency or with additional logistics modules. The cabin has suit port interfaces for supporting EVA, a grappling manipulator to dock or anchor on asteroid, dexterous
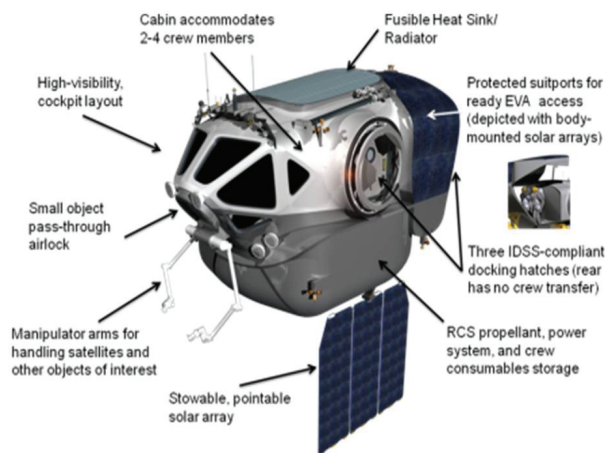
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Cabin accommodates 2-4 crew members

Fusible Heat Sink/Radiator

High-visibility, cockpit layout

Protected suitports for ready EVA access (depicted with body-mounted solar arrays)

Small object pass-through airlock

Three IDSS-compliant docking hatches (rear has no crew transfer)

Manipulator arms for handling satellites and other objects of interest

RCS propellant, power system, and crew consumables storage

Stowable, pointable solar array

Figure 10. *MMSEV Concept Image*

arms for sampling and servicing functions, solar arrays for power generation, an RCS system for local motion control, and iLIDS docking interfaces to mate with other spacecraft.

Sensors include depth mapping radar, LIDAR, and multispectral imagers. Mobility requires a full 6 axis RCS motion control system, but with limited delta V for only local navigation. Manipulation requires grappling that will likely be customized for ISS, Satellites or asteroid missions, and smaller arms for dexterous manipulation like sampling, servicing and carrying objects. Human interfaces include cockpit controls (displays, joysticks, audio), EVA interfaces, and remote interfaces for flying and operating the MMSEV as an unmanned vehicle. Autonomy includes the full range of spacecraft systems automation, as well as support for flying, manipulation, EVA support, and the rendezvous and docking required to mate the hatches with other vehicles. The Multi Mission Space Exploration Vehicle (MMSEV) will require onboard autonomous systems in order to achieve the reliability and affordability required by the President and Congress. The MMSEV will need autonomous systems to manage the spacecraft, requiring ground assistance only when a significant state change has occurred which affects mission success or when a state change has occurred beyond the limits of the onboard systems. Autonomous systems need to be able to minimize the need for operator assistance thereby limiting the size of ground based operations teams and minimizing operations costs.

2.3.2.4. Test HEO

The requirements for Robotics and Autonomy technologies to support near-term High Earth Orbit (HEO) missions will focus on the autonomous capabilities necessary to operate outside of

real-time control and support from the Earth. For missions to Lagrange Points, lunar orbit and near-vicinity NEAs, robotics and autonomous systems work will focus enabling robotic capabilities to perform precursor exploration and autonomous operations in support of the Crew. The evolution in robotics and autonomous systems capability for high earth orbit will focus on crew-system autonomy to support exploration in uncertain and dynamic environments.

2.3.2.5. Human HEO

Low-thrust, solar electric vehicles will travel from low-earth to a High Earth Orbit (HEO) carrying cargo using autonomous guidance, navigation and control to orient the electric propulsion system over the continuous thrusting period. Autonomy will be required to manage the complex spacecraft's system state. To dock with the cargo, autonomous rendezvous and docking will be required at the beginning and end of the HEO transfer.

The Human Rated Autonomy may be essential for Human HEO missions. Limited crew sizes and the need to abort to Earth require proactive autonomous systems to manage the vehicle. These capabilities require unambiguous determination of vehicle states, quick response to vehicle anomalies, and the ability to abort the crew to Earth well in advance of life threatening failures. Autonomous systems will need to implement vehicle state determination, diagnostics, prognostics, mission executives, and mission planning functions. Radiation hardened avionics will be necessary to ensure the vehicle can maintain crew functions during solar radiation events. A variety of intelligent algorithms will need to be integrated to accomplish these functions. New verification and validation methods will also be required for these human rated autonomy and automated functions.

2.3.2.6. HEO Utilization Flight 1

2.3.2.7. HEO Utilization Flight 2

For flexible human mission architectures, the crewed vehicle will require several basic on-board capabilities in order to complete the fundamental scientific and technical objectives. As missions explore farther and farther from the Earth, going to Earth-Moon Lagrange points, then Sun-Earth Lagrange points, and onward to Near Earth Objects (NEOs), the crew will need to be increasingly autonomous (see Section 2.3.2.5) from the Earth. The crew and spacecraft systems will need to be operationally autonomous from real-time ground

control support due to distance based communications delays. Proximity operations to any targets (space telescopes, or small NEAs) will require autonomous rendezvous and coupling technologies. This would require significant on-board capabilities beyond what has been planned for low-earth orbit or even lunar missions. The crew would need to have the equivalent of flight directors on-board to support real-time operations, EVA, robotic systems, and Proximity Ops. In addition, the crew would be a scientific vanguard to the destination (Lagrange Points, NEOs, etc), needing all the equipment and tools of any first explorers.

2.3.2.8. Near Earth Asteroid Human Mission

The first human mission to an asteroid will challenge our ability to live and work in deep space, perform EVA in space, rendezvous with distant objects, and support an independent crew working far from Earth (see Figure 11). The mission will begin with stack assembly, likely even with heavy launch capability. Trans-rock injection will be followed by a lengthy cruise phase, then insertion and rendezvous with the asteroid's orbit. Depending on the scale of the asteroid, proximity operations may have little in common with orbiting a planet, but more like hovering next to a satellite or other small object. Crew-centered operations will be the norm rather than the exception here. Mission control will be in an advisory function due to light-time communication delays. On-board automation must exist to support the crew operations for the mission. The crew will perform mapping and survey tasks, and then attempt to make contact with the asteroid surface with either their spacecraft or going EVA. Trans-Earth injection will be followed by a second lengthy cruise phase, then Earth capture and re entry.

All mapping and sensing technologies developed for precursors will be reused with refinement; then

Figure 11. *Concepts for a Human Asteroid Mission*

added to sensors and perception associated with supporting crew. Mobility needs include spacecraft 6 axis motion as well as EVA mobility for crew in a micro gravity environment. The mission will need manipulation technology for stack assembly, grappling and anchoring to an asteroid, EVA crew positioning, and sample handling. The human interfaces will span the spectrum of Earth supervision, cockpit command and control, and EVA suit interfaces. The crew will be required to operate their spacecraft far from Earth, so autonomy will be needed to reduce the system overhead and make the crew independent. The ability to reconfigure vehicle systems to maintain the crew in the event of major system losses will need to be addressed. New verification and validation methods will also be required for these human rated autonomy and automated functions. These abilities build on the requirements for the HEO missions. Multiple autonomous rendezvous and docking steps are likely, from stack assembly to proximity ops, and ranging from near earth locations to deep space docking.

2.3.2.9. Human Mars Orbit/Phobos

For a Human mission to Phobos or Mars Orbit, requirements for robotics and autonomy would involve equipment and techniques supporting remote sensing, deployment/re-deployment of robotic surface experiment packages, and robotic surface sampling. Previous ground-based observations and precursor mission data should have adequately characterized the surface and local space environment to reduce risk to the spacecraft and its assets (i.e., the crew and equipment). Hence, the majority of spacecraft operations should be able to take place in close proximity (~a few to several hundred meters) to the surface of Phobos. Such operations have been found to be challenging for remotely controlled spacecraft due to round trip light delay times of several tens of seconds or minutes, but should be much more tractable for the crew with humans directly in the loop. The crew and spacecraft should be able to match the rotation of Phobos, or hover over its surface, while maintaining a stable attitude from which they can conduct a detailed scientific exploration of the surface. This capability will ideally have been validated during a crewed NEO mission previously. Proximity operations and automated rendezvous technologies will be critical. Additional autonomous systems technology needs become more demanding with missions to Mars orbit, Phobos, Deimos, more remote NEAs and

Venus orbit. Automation to support cryogenic fluid management for long-duration transfer and management of liquid hydrogen, other propellants and life support fluids, and ECLSS systems will be needed as well. Autonomy and other functions will build upon capabilities cited as essential for the previous missions to HEO and asteroids.

2.3.2.10. Human Mars Mission

There is much debate about the path to Mars, but general agreement that Mars is the ultimate destination for humans in the inner solar system (see Figure 12). Volumes have been written on Mars mission architectures, and our science missions have greatly informed our plans with knowledge of the surface and experience in landing, operating and exploring. Standout differences between a human mission to Mars and our previous experiences are the long duration of the mission for crew, the combination of zero gravity and reduced gravity, the large scale of entry and descent vehicles, and long surface stay and mobility range required. A human mission to Mars may be preceded by missions to near Mars, its moons or Mars orbit.

Pre-deployed robotic assets could potentially be used to help produce propellant from the massive amounts of sub-surface water ice that are expected to be present. By excavating water ice from the regolith, oxygen and hydrogen propellant can be produced by electrolysis without transporting hydrogen to Mars, as is needed for the production of Methane. Landing pads may be robotically prepared to reduce the risk of a bad landing. Robotic assistants can connect the crew lander to a power plant by deploying and mating a power cable to the power plant before the lander runs out of stored power. The robots will use sunlight energy for solar electric propulsion, and then the humans will use the propellants that are produced by the robotic mining systems. This is a good example of enabling human-robotic exploration.

Human missions generate massive amounts of data, and humans augmented with sensors are now the baseline for exploration. Mapping, science in-struments, biomedical instruments, and sensors to support navigation and mobility will be required with redundancy in numbers and type. Mobility will include in-space flying, surface roving, and EVA mobility. The crew will be far from Earth and will need interfaces to all systems, and those systems will be highly autonomous to avoid consuming crew time. Autonomous systems will need to integrate across vehicle stages or platforms. The Human Mars vehicle will have a complicated configuration including aerocapture, landers, and ascent stage recovery. The mission will involve complex stack assembly with manipulation, grappling, rendezvous and docking, EVA/robotic assembly, and must be able to conduct those operations either near Earth, in deep space, Mars orbit, or on the surface.

2.3.3. SMD Missions

2.3.3.1. Mars Science Laboratory (MSL)/ Extended

Extended phases of the MSL mission are opportunities for insertion and testing of software upgrades representing technology push items. Examples of potential new onboard capabilities include faster implementations of visual odometry algorithms for slip estimation, onboard visual terrain classification for improved path planning, estimating parameters of soil mechanics models for improved trafficability analysis, automated mid-sol and end-of-sol position estimation using orbital imagery, automated instrument pointing, science operations while driving, and automated site survey and downlink of site maps annotated with science observations. Some functions currently performed on the ground could be migrated onboard, including motion planning and collision checking for the sampling arm. Since MSL is powered by RTGs, not solar panels, new operational modes could include driving in the dark through terrain determined in advance to be free of obstacles by examination of onboard and orbital sensor data.

Technology push opportunities exist for uploading new perception software, that while utilizing the existing sensors, will expand capabilities and productivity per sol. Software upgrades can also provide for improved mobility and manipulation performance. Autonomy upgrades include more efficient data handling, and fault detection and recovery.
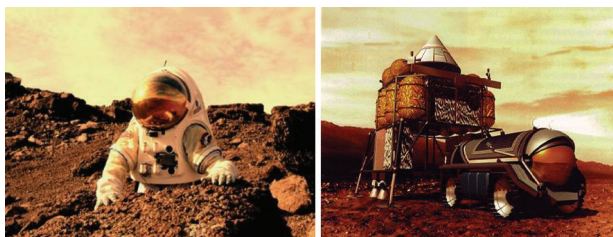

Figure 12. *Human Mars Mission Concepts*

2.3.3.2. Mars Sample Return (MSR) Mission 1

2.3.3.3. MSR 2

2.3.3.4. MSR 3

A definitive answer to whether there is or has been life on Mars or, if not, why not, requires return of carefully selected samples from one or more well-characterized, high-priority sites. Analysis of returned samples allows measurements using complex analytical techniques (i.e., occupying large laboratories), provides necessary opportunities for follow-up measurements, and enables subsequent analyses using techniques not yet developed at the time of sample return. Properly interpreting evidence related to life requires multiple approaches, and it is not possible to select discrete and unique criteria ahead of time. Answers will come only through multiple analyses of returned samples. Analysis of returned samples would also contribute to most disciplines at Mars and is necessary for advancing our understanding of many of them, including through comparison with Earth. There is high relevance to topics including planetary formation, geophysical evolution, surface geology, climate and climate history of all the terrestrial planets.

Sample return is also thought to be a necessary step along the path toward potential human missions to Mars, in order to understand the environment prior to human arrival.

The proposed MSR would be a campaign of three missions:

1. 2018: sample caching mission, which would cache rock cores for later retrieval.

2. 2022: MSR Orbiter Mission, which would augment the planetary communications network and return the orbiting sample container (OS) to the Earth's surface after 2024.

3. 2024: MSR Lander Mission, which would retrieve the sample and places it in Mars orbit in an orbiting sample container (OS).

A fourth component is the Mars Returned Sample Handling element that would include a Sample Receiving Facility (SRF) and a curation facility.

The campaign would entail three launches. The current baseline for the first mission is the Joint NASA/ESA Mars 2018 mission, which would use a Mars Science Laboratory (MSL)-style entry, descent, and landing (EDL) system to land both a NASA Caching Rover and the ESA ExoMars Rover on a single platform. The proposed MSR Orbiter would be sent nominally two opportunities (four years) later. It is projected to launch before the MSR Lander, so that it could provide telecommunications infrastructure for the lander and its fetch rover and Mars Ascent Vehicle (MAV). In the next opportunity (two years later), the MSR Lander would be sent, also using an MSL-style EDL system to get the lander platform, including the MAV, to the surface. The lander would dispatch a fetch rover to retrieve a sample cache previously deposited on the surface by the 2018 NASA Caching Rover. The cache would be augmented by a lander-collected sample and inserted into the OS that would be launched into a 500 km orbit by the MAV. The orbiter—having monitored the launch and release of the OS—would rendezvous and capture the OS. On the orbiter the process of "breaking the chain of contact" with Mars would take place, sealing the OS into an Earth Entry Vehicle (EEV). The orbiter would then return to Earth, release the EEV a few hours before entry, and divert into a non-Earth return trajectory. Because of Planetary Protection requirements, the EEV seals would have to be verified before targeting the Earth. The EEV would hard land on the surface and then be transferred to a secure SRF for quarantine before samples are extracted.

All three MSR missions have a broad set of technology pull opportunities. MSR-1 Has potentially the most complex manipulation and mobility requirements of any mission yet attempted. This robot will need sensing and perception to assist Earth science teams and augment their visualization of the geologic units and transitions. Coupled with a long term mission life, the robot will be responsible for long term cache management. MSR-3 will perform the first Automated Rendezvous and Docking task ever attempted on the surface.

MSR Key Requirements

Numerous science advisory groups have met over the past decade to define proposed science objectives for MSR and to address the balance of objectives and mission difficulty and cost. While the science would be ultimately performed in laboratories here on Earth, the following goals reflect the latest thinking on the MSR missions.

- Return >500 g of sample consisting of:
  - » 1. Rock cores from multiple geological units
  - » 2. Regolith from a single location, but potentially from multiple locations
  - » 3. A compressed atmospheric sample

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- Use a suite of in situ instrumentation to carefully select coring targets and document context of the cores
- Minimize organic and inorganic contamination
- Package samples to minimize cross contamination and sample alteration (which might or might not include hermetic sealing)
- Maintain temperature control of samples to <20°C (except potentially higher for a short period after landing at Earth)

2.3.3.5. Comet Surface Sample Return (CSSR)

The fundamental CSSR mission scientific objectives are as follows:
- Acquire and return to Earth for laboratory analysis a macroscopic (at least 500 cc) sample from the surface of the nucleus of any comet.
- Collect the sample using a "soft" technique that preserves complex organics.
- Do not allow aqueous alteration of the sample at any time.
- Characterize the region sampled on the surface of the nucleus to establish its context.
- Analyze the sample using state-of-the-art laboratory techniques to determine the nature and complexity of cometary matter, thereby providing fundamental advances in our understanding of the origin of the solar system and the contribution of comets to the volatile inventory of the Earth.

The baseline CSSR mission scientific objectives will also provide revolutionary advances in cometary science:
- Capture gases evolved from the sample, maintaining their elemental and molecular integrity, and use isotopic abundances of the gases to determine whether comets supplied much of the Earth's volatile inventory, including water.
- Return material from a depth of at least 10 cm (at least 3 diurnal thermal skin depths), if the sampled region has shear strength no greater than 50 kPa, thereby probing compositional variation with depth below the surface.
- Determine whether the sample is from an active region of the nucleus because those areas may differ in composition from inactive areas.

After the mission spacecraft travels to Comet 67P/C-G and collects images to characterize the comet's nucleus, a sample return vehicle (SRV) will return ≥500 cc of material to Earth for laboratory analysis. The payload will collect the samples using 4 drills. Samples will be maintained during the return trip at ≤ –10°C. After SRV recovery, the samples will be transferred to Johnson Space Center astromaterials analytical laboratories that will have been upgraded with capabilities to store, analyze and characterize frozen samples. The reliance on heritage spacecraft design wherever possible is intended to minimize risk. The following critical technologies will require development to Technology Readiness Level (TRL) 6:
- Ballistic-type sample return vehicle (SRV) will require new mobility and control technologies.
- UltraFlex solar array Sample Acquisition System (SAS) will require new sensing technologies.
- Height and Motion System (H&MS) will require manipulation, sensing and control technologies.

2.3.3.6. Comet Nucleus Sample Return (CSNR)

SMD will propose a technological development program to enable a CNSR mission in the subsequent decade (2021–2030). This Technology Development Program will address technology needs for CNSR, mitigate mission development risks, and verify promising technologies and mission concepts via a test and evaluation program.

The overriding objective is to provide assurance that the key CNSR-required technologies can all be raised to at least Technology Readiness Level 5 (TRL 5, full-scale prototype testing) in the coming decade.

It is assumed that by the time a CNSR mission is launched, a Comet Surface Sample Return (CSSR) mission will have been accomplished and will have demonstrated how to obtain a surface sample. The primary interest for the CNSR mission is to obtain a sample at depth(s) from beneath the surface layer and to maintain it cold enough to return material to the Earth in the ice phase.

The following set of top-level science goals is assumed for the mission study with highlighted tech opportunities:
- *Floor:* Return one sample from a single site, with water ice and less volatile organics intact (i.e., no water ice melting or loss of "moderately volatile" species to vacuum). [manipulation and control technology]
- *Baseline:* Return one sample from a single site, with >20% water ice by mass, with water ice, most volatile organics preserved, and stratigraphy intact. (It is noted that the preservation of stratigraphy is highly desired, but it is recognized to be difficult to achieve). [sensing, perception and manipulation

technology]

- *Desired:* Return up to several kilograms of samples from multiple sites on the nucleus, with stratigraphy and all ices intact, and no cross-contamination of collected samples. [sensing, perception, manipulation and mobility technology]

2.3.3.7. Venus Mobile Explorer (VME, aka Venus Aerobot)

The Venus Mobile Explorer (VME) mission concept affords unique science opportunities and vantage points not previously attainable at Venus. The ability to characterize the surface composition and mineralogy in two locations within the Venus highlands (or volcanic regions) will provide essential new constraints on the origin of crustal material, the history of water in Venus' past, and the variability of the surface composition within the unexplored Venusian highlands. As the VME floats (~3 km above the surface) between the two surface locations, it offers new, high spatial resolution, views of the surface at near infrared (IR) wavelengths. These data provide insights into the processes that have contributed to the evolution of the Venus surface. The science objectives are achieved by a nominal payload that conducts in situ measurements of noble and trace gases in the atmosphere, conducts elemental chemistry and mineralogy at two surface locations separated by ~8–16 km, images the surface on descent and along the airborne traverse connecting the two surface locations, measures physical attributes of the atmosphere, and detects potential signatures of a crustal dipole magnetic field.

The VME design includes an elegant, volume efficient cylindrical gondola to accommodate the science payload in a thermally controlled environment. An innovative, highly compact design surrounds the gondola with a toroidal pressure tank capped with the bellows, enabling the entire lander system to fit in an aeroshell with heritage geometry. The thermal design uses heat pipes and phase change material that enable the gondola electronics and instruments to survive 5 hours near the Venus surface, thus providing sufficient time for surface chemistry and an aerial traverse >8 km in the current- like winds.

Launched on an Atlas V 551 in either 2021 or 2023, the carrier spacecraft carries the VME probe to Venus on a Type II trajectory. After release from the carrier, the VME probe enters the atmosphere, descends on a parachute briefly, and then free-falls to the surface. Science is conducted on descent and at the surface. While collecting data at the first site, the bellows are filled with helium and when buoyant, rise with the gondola, leaving the helium pressure tank on the surface. Driven by the ambient winds, the gondola floats with the bellows for ~220 minutes, conducting additional science. At the completion of the 8–16 km aerial traverse, the bellows are jettisoned and the gondola free falls back to the surface, where final surface science measurements are performed. The total mission time in the Venus atmosphere is 6 hours, which includes 5 hours in the near surface environment. The VME probe transmits data to the flyby carrier spacecraft continuously throughout the 6-hour science mission. After losing contact with the VME probe, the carrier spacecraft then relays all data back to Earth.

This mission represents a completely new approach to surface exploration. Technology needs span sensing, perception, mobility, sample manipulation, and spacecraft autonomy.

2.3.3.8. Titan Aerobot

A mission launched in the 2018–2022 timeframe would provide a unique opportunity to measure a seasonal phase complementary to that observed by Voyager and by Cassini, including its extended missions.

Recent discoveries of the complex interactions of Titan's atmosphere with the surface, interior, and space environment demand focused and enduring observation over a range of temporal and spatial scales. The Titan Saturn System Mission (TSSM) two-year orbital mission at Titan would sample the diverse and dynamic conditions in the ionosphere where complex organic chemistry begins, observe seasonal changes in the atmosphere, and make global near-infrared and radar altimetric maps of the surface. This study of Titan from orbit with better instruments has the potential of achieving a 2–3 order-of-magnitude increase in Titan science return over that of the Cassini mission. Chemical processes begin in Titan's upper atmosphere and could be extensively sampled by an orbiting spacecraft alone. However, there is substantial additional benefit of extending the measurements to Titan's lower atmosphere and the surface. Titan's surface may replicate key steps toward the synthesis of prebiotic molecules that may have been present on the early Earth as precursors to life. In situ chemical analysis, both in the atmosphere and on the surface, would enable the assessment of the kinds of chemical species that are present on the surface and of how far such pu-

tative reactions have advanced. The rich inventory of complex organic molecules that are known or suspected to be present at the surface makes new astrobiological insights inevitable. In situ elements also enable powerful techniques such as subsurface sounding to be applied to exploring Titan's interior structure. Understanding the forces that shape Titan's diverse landscape benefits from detailed investigations of various terrain types at different locations, a demanding requirement anywhere else, but one that is uniquely straightforward at Titan using a Montgolfière hot-air balloon. TSSM's Montgolfière could circumnavigate Titan carried by winds, exploring with high resolution cameras and subsurface-probing radar. The combination of orbiting and in situ elements is a powerful and, for Titan, unprecedented opportunity for synergistic investigations— synthesis of data from these carefully selected instrumentation suites is the path to understanding this profoundly complex body.

The flight elements would be launched on an Atlas V 551 launch vehicle in 2020 using a gravity-assist SEP trajectory to achieve a trip time of 9 years to Saturn. Following Saturn orbit insertion, the orbiter would conduct a Saturn system tour, including 7 close Enceladus flybys and 16 Titan flybys. This phase would allow excellent opportunities to observe Saturn, multiple icy moons and the complex interaction between Titan and Saturn's magnetosphere. The Montgolfière would be released on the first Titan flyby, after Saturn orbit insertion, and would use an X-band relay link with the orbiter for communications. The lander would be released on the second Titan flyby and communicate with the orbiter during the flyby only. This 24-month period would also mark the mission phase when all of the Titan in situ data is relayed back to Earth. Following its tour of the Saturn system, the orbiter would enter into a highly elliptical Titan orbit to conduct a two-month concurrent Aerosampling and Aerobraking Phase in Titan's atmosphere, sampling altitudes as low as 600 km. The orbiter would then execute a final periapsis raise burn to achieve a 1500-km circular, 85° polar-mapping orbit. This Circular Orbit Phase would last 20 months.

This mission represents a completely new approach to surface exploration. Technology needs span sensing, perception, mobility, sample manipulation, and spacecraft autonomy.

2.3.3.9. Additional SMD Missions

The RTA panel is continuing to investigate additional missions that will provide both push and pull technology opportunities for robotics, telerobotics and autonomous systems technology. These include:

- Europa Lander
- Venus Sample Return
- ATLAST
- 30m Space Telescope

2.3.4. ARMD Missions

2.3.4.1. Small UAV

Small UAV Unmanned Aerial Vehicles (UAVs) are aircraft that are either fully- or semi-autonomous (mixed initiative) robotic vehicles. UAVs are fundamentally similar in concept to spacecraft. They are used for NASA science missions in uncertain and rapidly changing environments, and they drive much the same set of autonomy requirements (pilot automated monitoring, diagnosis, planning and execution, reliable software, and advanced controls) that NASA finds in inter-planetary exploration missions. Additionally, they can naturally be used to investigate issues in multi-agent cooperation (e.g., for surveillance by fleets of UAVs, or planetary robots) that NASA will need to solve for various future missions.
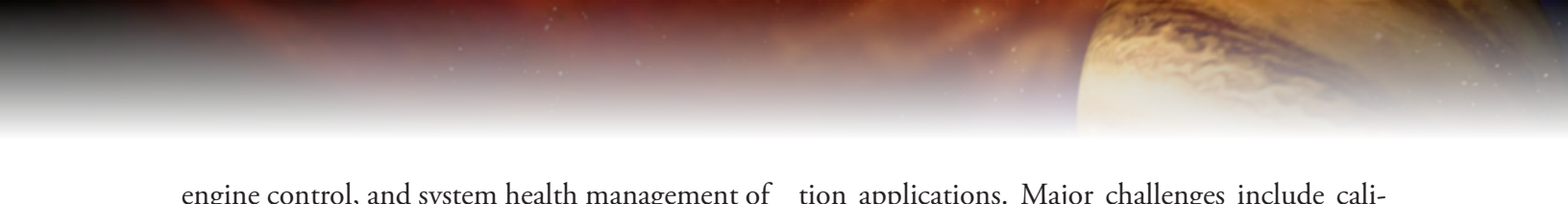
2.3.4.2. Wind Turbines

Many challenges exist for the efficient and safe operation of wind turbines due to the difficulty in creating accurate models of their dynamic characteristics and the turbulent conditions in which they operate. A promising new area of wind turbine research is the application of adaptive control techniques, which are well suited to problems where the system model is not well known and the operating conditions are unpredictable.

2.3.4.3. Wildfire UAV

Full automation of the Wildfire UAV system will enable free-flight within the National Airspace. This included the autonomous filing of flight plans and execution of the same, based upon satellite sensor data indicating where fires exist in a geographic area. On-board system health management and adaptive control will enable the UAV to operate in degraded modes. On-board data analysis and science discovery will permit the UAV to report operational fire targets to ground firefighters and to support remote sensing of fire progress.

2.3.4.4. Air Cargo

Advanced adaptive control technologies and system state monitoring and management capabilities will be required to enable real-time feathering,

engine control, and system health management of variable speed rotorcraft operations. V&V of the flight critical systems will also be necessary.

3. CONCLUSIONS

3.1. Top Technical Challenges

The RTA panel identified multiple top technical challenges, and these will be described in order of their associated location in the WBS, not a particular priority. Each represents the top priority within its WBS sub topic.

Object Recognition and Pose Estimation

Object recognition requires sensing, often fusing multiple sensing modalities, with a perception function that can associate the sensed object with an object that is understood a priori. Sensing approaches to date have combined machine vision, stereo vision, LIDAR, structured light, and RADAR. Perception approaches often start with CAD models or models created by a scan with the same sensors that will be used to identify the object later. Pose estimation seeks to locate an object relative to a sensor coordinate frame, computing the six axis pose using sensing data. Pose estimation is often preceded by object recognition, or presumes an object so that its pose can be estimated and tracked. There is a special case of identifying humans as objects of interest, tracking human motion, gestures, and doing human recognition. Major challenges include the ability to work with a large "library" of known objects (>100), identifying objects that are partially occluded, sensing in poor (high, low and sharply contrasting) lighting, estimating the pose of quickly tumbling objects, and working with objects at near and far range. This technology is important for object manipulation and in mobility for object following and avoidance. Human tracking is important in manipulation for safely working with human teammates, and in mobility for avoiding collisions with pedestrians.

Fusing vision, tactile and force control for manipulation

The field of mobile robotics has matured with the advance of safe, fast and deterministic motion control. This success has come from fusing many sensors to avoid contacting hazards. Manipulation requires forming contact, so the breadth of sensing will require proximity, then tactile, and ultimately force sensing to reach, grasp and use objects like tools. Vision requires sensors that are not blocked when limbs reach for objects, but that can be pointed and transported for mobile manipulation applications. Major challenges include calibration of highly dissimilar sensors, dissimilar resolution, noise, and 1st principles of physics in the development of new sensors.

Achieving human-like performance for piloting vehicles

Machine systems have the potential to outperform humans in endurance, response time and number of machines that can be controlled simultaneously. Humans have safety limits on flight or drive-time that do not exist in machines. Human response time, coupled with human machine interfaces, results in significant delays when faced with emergency conditions. Humans are poor at parallel processing the data and command cycles of more than a single system. But machines are currently far behind humans in handling extremely rare cases, improvising solutions to new conditions never anticipated, and learning new skills on the fly.

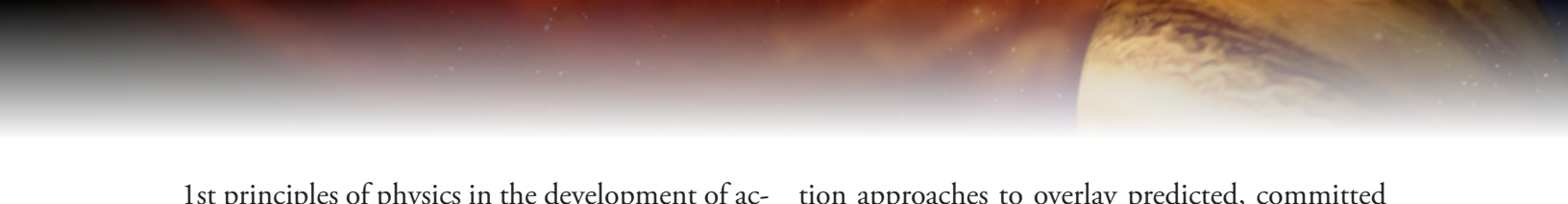### Access to extreme terrain in zero, micro and reduced gravity

Current crew rovers cannot access extreme Lunar or Martian terrain, requiring humans to park and travel on foot in suits. In micro gravity, locomotion techniques on or near asteroids and comets are undeveloped and untested. Access to complex space structures like the ISS is limited to climbing or positioning with the SSRMS. Challenges include developing robots to travel into these otherwise denied areas, or building crew mobility systems to move humans into these challenging locations.

Grappling and anchoring to asteroids and non cooperating objects

Grappling an object in space requires a manipulator or docking mechanisms that form a bi directional 6 axis grasp. Grappling an asteroid and then anchoring to it is an all-new technology. Grappling approaches attempted on man-made objects may not apply to asteroids, since these techniques count on specific features such as engine bells that will not be available on a natural object. Similarly, grappling an object that is tumbling has not been attempted.

Exceeding human-like dexterous manipulation

The human hand is generally capable. A robotic equivalent, or superior, grasping ability would avoid the added complexity of robot interfaces on objects, and provide a sensate tool change-out capability for specialized tasks. Dexterity can be measured by range of grasp types, scale, strength and reliability. Challenges include fundamental

1st principles of physics in the development of actuation and sensing. Other challenges include 2 point discrimination, contact localization, extrinsic and intrinsic actuation, backdrivability vs compliance, speed/strength/power, hand/glove coverings that do not attenuate sensors/motion but are rugged when handling rough and sharp objects.

Full immersion, telepresence with haptic and multi modal sensor feedback

Telepresence is the condition of a human feeling they are physically at a remote site where a robot is working. Technologies that can contribute to this condition include fully immersive displays, sound, touch and even smell. Challenges include 1st principles of physics in the development of systems that can apply forces to human fingers, displays that can be endured for long periods of telepresence immersion, and systems that can be used by people while walking or working with equipment concurrently with the telepresence tasks.

Understanding and expressing intent between humans and robots

Autonomous robots have complex logical states, control modes, and conditions. These states are not easily understood or anticipated by humans working with the machines. Lights and sounds are helpful in giving cues as to state, but need to be augmented with socially acceptable behaviors that do not require advanced training to interpret. Likewise, robots have difficulty in understanding human intent through gesture, gaze direction or other expressions of the human's planned behavior.

Verification of Autonomous Systems

Large software projects have such complex software that exhaustive and manual exploration of all possible cases is not feasible. Human rated autonomous systems are particularly challenging. Verification techniques are needed to more fully confirm system behavior in all conditions.

Supervised autonomy of force/contact tasks across time delay

Tasks have time constants that vary greatly, with the shortest time constants involving motions that form contacts with the environment and force controlled actions. These tasks require high speed local control loops. As time delays approach these tasks time constants the ability to tele-operate the machine degrades. Supervision is the management of a robot with autonomous skills, working along a sequence of tasks. Challenges include run time simulation to predict future states, visualiza-

tion approaches to overlay predicted, committed and commanded states, and the ability to work ahead of real-time.

Rendezvous, proximity operations and docking in extreme conditions

Rendezvous missions include flybys of destinations without landing or docking. Proximity operations require loiter at destinations with zero relative velocity. Docking drives latching mechanisms and electrical/fluid couplings into a mated condition. Major challenges include the ability to rendezvous and dock in all ranges of lighting, work across near to far range, and achieve a docked state in all cases.

Mobile manipulation that is safe for working with and near humans

Merging manipulative capabilities with general mobility is sought to allow robots to go to the work site, rather than require the work be delivered to the robot. Manipulator arms and mobility drives each pose hazards to people. Combined, they present many risks. Challenges include tracking humans in the workspace, responding deterministically to inadvertent contact, compliance, and providing redundant sensor and software systems.

3.2. Overlap with other Technical Areas.

Table 1 summarizes overlaps that have been identified with between TA4 and the other technology areas. These have been sorted into the two classes of either being technologies needed by TA4, or technologies from TA4 needed by the other area.

3.3. Summary of Findings for Robotics, Tele-Robotics and Autonomous Systems

1) NASA's four Mission Directorates are depending on Robotics, Tele-Robotics and Autonomy Technology.

2) Technology should aim to exceed human performance in sensing, piloting, driving, manipulating, rendezvous and docking.

3) Technology should target cooperative and safe human interfaces to form human-robot teams.

4) Autonomy should make human crews independent from Earth and robotic missions more capable.

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Table 1. *Overlap with other Technical Areas showing technologies needed by TA4 and technologies from TA4 needed by the other area.*

Area ID	Area Name	Needed By RTA TA4	Provided By RTA TA4
TA1	Launch Systems	RTA System Delivery	Health Management, Abort Systems
TA2	In-Space Propulsion	RTA System Delivery	Controlled Formation and Docking
TA3	Space Power	High Specific Power and Energy	Offloading, Setup, Maintenance
TA5	Comm and Nav	High Throughput, Bi-dir comm, RF Nav	(Re)Deployment and maintenance,
TA6	Human Health, Life Support and Habitation		System health, Automation
TA7	Human Exploration Destination Systems		Robot and Autonomy Applications
TA8	Science Observatories, Instruments, Sensors		Data Mining, Assembly, Servicing
TA9	Entry Descent and Landing	RTA System Delivery	Precision Landing, Hazard Avoidance, Autonomy
TA10	Nanotech	Advanced Materials, Sensors, Actuators	
TA11	Modeling, Sim, IT and Processing	Computing, Physics Based Models	RTA System Design Data, Test Results
TA12	Materials, Structure, Mechanisms and Manufacturing	Docking Mechanisms, Mechanical Interfaces	Robotic Manufacturing in Space
TA13	Ground and launch processing	RTA System Processing	Robotic Launch Equipment, Mars Ground Processing, Curation
TA14	Thermal Management Systems	RTA System Thermal Control	Deployment, Servicing, Cleaning

ACRONYMS

AERCam — Autonomous EVA Robotic Camera
ARC — Ames Research Center
AR&D — Autonomous Rendezvous and Docking
ARMD — Aeronautics Research Mission Directorate
ATP — Authority to proceed
ATV — Autonomous Transfer Vehicle
CTV — Crew Transfer Vehicle
ESMD — Exploration Systems Mission Directorate
EVA — Extra Vehicular Activity
DPP — Dexterous Pointing Payload
DRM — Design Reference Mission
FPGA — Field Programmable Gate Array
FSW — Flight Software
GEO — Geosynchronous Earth Orbit
GN&C — Guidance, Navigations and Control
GSFC — Goddard Space Flight Center
HEFT — Human Exploration Framework Team
HEO — High Earth Orbit
HST — Hubble Space Telescope
HTV — H-II Transfer Vehicle
ILIDS — International Low Impact Docking System
ISS — International Space Station
IVA — Intra Vehicular Activity
JPL — Jet Propulsion Laboratory
JSC — Johnson Space Center

LEO — Low Earth Orbit
LIDAR — Light Detection and Ranging
LIDS — Low Impact Docking System
MER — Mars Exploration Rover
MMU — Manned Maneuvering Unit
MSL — Mars Science Laboratory
MSR — Mars Sample Return
MMSEV — Multi Mission Space Exploration Vehicle
NEA — Near Earth Asteroid
NEAR — Near Earth Asteroid Rendezvous
NEO — Near Earth Object
NRE — Non recoverable Engineering
OCT — NASA's Office of the Chief Technologist
ORU — Orbital Replacement Unit
OTCM — ORU Tool Changeout Mechanism
R2 — Robonaut 2
R2D2 — Robotic Refueling Dexterous Demonstration
RMCT — Robotic Micro Conical Tool
RTAs — Robotics, Tele-Robotics and Autonomous systems
RWS — Robotics Work Station
SAFER — Simplified Aid for EVA Rescue
SMD — Science Mission Directorate

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SOMD   Space Operations Mission Directorate
SPDM   Special Purpose Dexterous Manipulator
SRMS   Shuttle Remote Manipulator System
SSRMS Space Stations Remote Manipulator
       System
TA   Technology Area
TRL   Technology Readiness Level
TSSM   Titan Saturn System Mission
UAV   Unmanned Aerial Vehicle
V&V   Verification and Validation
WBS   Work Breakdown Structure

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